Maneuver Design for the Galileo VEEGA Trajectory

Christopher L. Potts [†], Michael G. Wilson [†]
Clifford E. Helfrich [†], and Ido Dubrawsky [†]

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Introduction.

After more than three years of space flight, the Galileo spacecraft is now on a direct trajectory to its final destination, Jupiter. It's taken three planetary gravity assists to obtain the energy necessary for Galileo to intercept Jupiter in its orbit. This Venus-Earth-Earth sequence of gravity assists is referred to as the VEEGA trajectory. Each gravity assist requires precise spacecraft delivery to propel Galileo o:n the proper path to the next encounter. This paper will address the analysis, constraints, anti design evolution of trajectory correction maneuvers (TCMs) which have enabled the successful completion of the circuitous VEEGA trajectory (Figure 1) and along the way also provided the first encounter with a main-belt asteroid, Gaspra.
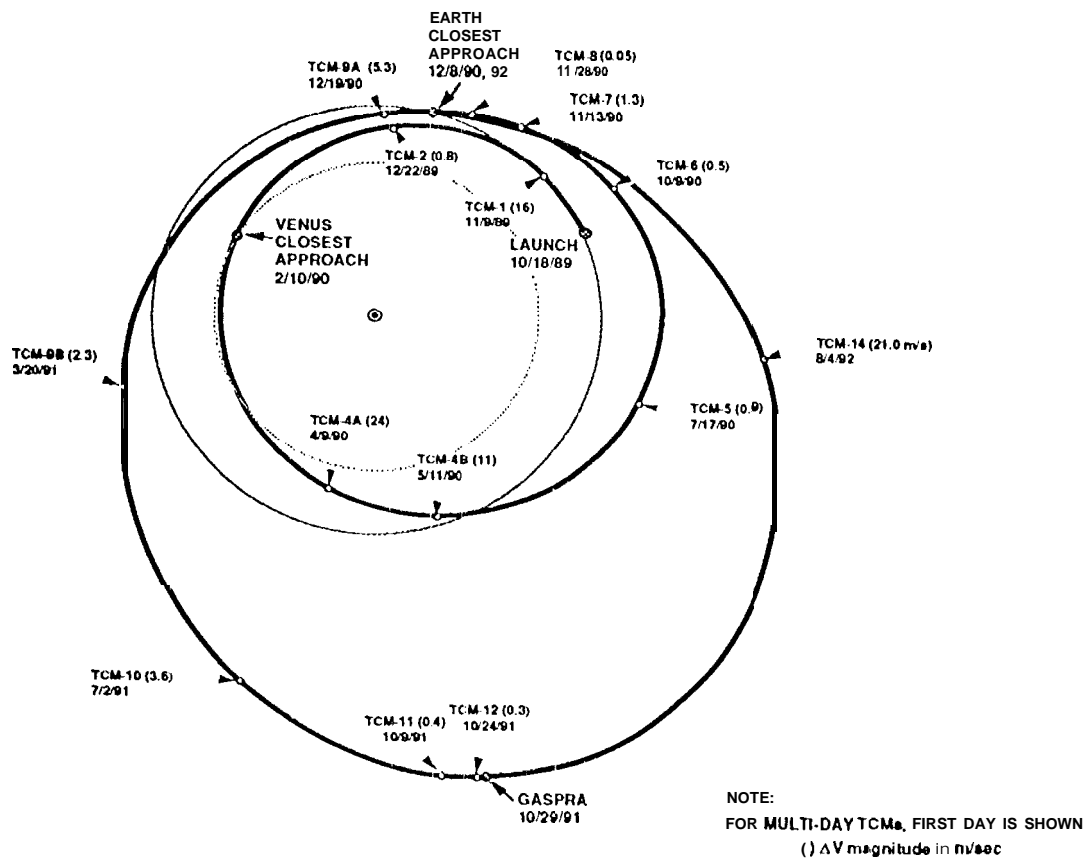

Figure 1: Galileo VEEGA Trajectory Correction Maneuvers

† Member of Technical Staff, Navigation Systems Section

Maneuver Design Philosophy

A common objective of each trajectory correction maneuver is to minimize the consumption of propellant. At launch, the Galileo spacecraft mass was 2717 kg, which included 925 kg of usable propellant. At that time, the amount of usable propellant remaining after completing the Jupiter orbital tour often targeted satellite encounters was predicted to be approximately -56 kg at the 90% probability level. This is the definition of the Galileo propellant margin, PM. Although the propellant margin has increased dramatically since launch (currently -3 kg), it is safe to assume that propellant will always be a carefully monitored and very valuable consumable for the Galileo project. Consequently, it is standard practice for each TCM design to apply trajectory optimization techniques to minimize the propellant required while at the same time satisfying all applicable constraints.

The reality of TCM design is that there are many constraints which must be met besides remaining on the proper trajectory to Jupiter. First and foremost among these are Earth navigation constraints. Prior to launch a very thorough and detailed analysis was completed specifying all navigation constraints required to ensure a safe flyby of Earth by the radioisotope thermoelectric generator (RTG) powered Galileo spacecraft. TCMs preparing for each gravity assist (even TCM-1 prior to Venus) had to be biased in order to ensure that all conceivable spacecraft faults would not place Galileo on an Earth impacting trajectory. Earth navigation constraints and their effect on maneuver design will be discussed. With the VEEGA trajectory came additional thermal constraints due to the extended periods Galileo would spend within 1. AU of the sun. Consequently, Galileo has spent much time nearly sun-pointed in order to shade its bus from solar radiation. As a results, many TCMS also had to be executed at a sun-point attitude in the interest of spacecraft health anti safety. Another irnplementation constraint exists as a result of the need to pulse the thrusters in order to protect them against overheating. This constraint results in the implementation of large TCMs extending over multiple days. Iterative techniques are utilized to properly model the TCM implementation using existing software. Targeting constraints at encounter bodies develop in an effort to maximize science return. The proper encounter aimpoint and arrival time can provide the maximum illuminated area for high priority asteroid observations, or dual Deep Space Network (DSN) station coverage to protect the downlink telemetry. All such constraints must be satisfied by the TCM design while using as little propellant as possible.

Propellant Utilization

A useful metric for measuring the success of the TCM design goal to save propellant is a comparison. of actual propellant used in the mission to pre-launch estimates. Through the completion of TCM-14 on August 7, 1992, the actual TCM propellant expenditure was 87 kg of which 75 kg were deterministic and the remaining 12 kg statistical. Pre-launch, the mean estimate for the statistical TCM propellant was 27 kg with a 99% upper limit of 55 kg, Hence the post TCM-14 statistical propellant usage is less than half of the pre-launch predicted mean and only 21% of the 99% upper limit. These values illustrate the success level Galileo is achieving in all areas of TCM design: orbit determination, trajectory design, maneuver design, and spacecraft performance.

There are some key events that are responsible for this saving of statistical propellant. A flawless shuttle launch combined with a very accurate Inertial Upper Stage injection to Venus saved approximately 3 kg of propellant margin. TCM-2 was so accurate that the final maneuver before the Venus gravity assist, TCM-3, was canceled. The achieved b-plane encounter point for the Earth 1 gravity assist was only 8 km from the ideal aimpoint and the time of closest approach was late by just 0.2 second s. This exceptional flyby accuracy saved about 10 kg of propellant margin with respect to pre-launch estimates. TCM-13 was scheduled to occur after the Gaspra encounter, but was determined unnecessary. The second Earth gravity assist proved even more accurate than the first with only a 1.4 km b-plane miss and just 0.1 seconds early in arrival time. As a result of such a precise flyby, the TCM scheduled thirteen days after EGA2 (TCM-18) was deemed unnecessary.

Future Events

Galileo will encounter its second asteroid, Ida, on August 28, 1993. Two maneuvers are scheduled to provide ideal encounter condition for science. These maneuvers are scheduled to occur fifteen and three days before Ida closest approach. TCM-22 occurs nearly one month after the Ida flyby and targets to Jupiter. This 38 m/s velocity change is the largest deep space maneuver for Galileo. A particularly challenging event occurs 150 days before Jupiter. At this point the Galileo probe is released on a ballistic trajectory targeting to specific entry conditions at Jupiter. The 400 Newton engine will then be available to deflect the orbiter to pass in front of Io's path in order to remove energy from the spacecraft. Jupiter Orbit Insertion (J OI) takes place on December 8, 1995, with a 645 m/s velocity change. Near apojove, a 375 m/s maneuver is designed to raise perijove to approximately four Jupiter radii. The following twenty months are loaded with activity as thirty-one more TCMS are scheduled to complete the tour of the Galilean satellites.

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